Radiation effects in nanostructures: Comparison of proton irradiation induced changes on Quantum Dots and Quantum Wells.

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Successful implementation of technology using self-forming semiconductor Quantum Dots (QDs) has already demonstrated that temperature independent [1] Dirac-delta density of states [2] can be exploited in low current threshold QD lasers [3] and QD infrared photodetectors [4]. The possibility of using coupled quantum dots in the fabrication of cellular automata [5] might revolutionize computation technologies. Another technologically interesting application which is particular to self-assembled quantum dots would makes use of the naturally large broadening (inhomogeneous/homogeneous) ratios observed in their photoluminescence (PL) spectra, an ideal feature for frequency domain high density optical memories [6]. Minimizing the impact of radiation induced degradation in optoelectronic devices is important for several space applications, and protons in particular, pose a particularly severe threat to both planetary and Earth-orbiting spacecraft. Here we compare the photoluminescence (PL) emission from equivalent InGaAs/GaAs Quantum Well (QW) and QD structures after controlled irradiation with 1.5 MeV. Our results show a significant enhancement in radiation tolerance with three-dimensional quantum confinement.
Some additional radiation induced changes in photo-carrier recombination from QDs include a slight increase in PL emission with low and intermediate proton doses, which are tentatively attributed to reduction of the phonon bottleneck by defect assisted phonon emission [7]. Additional relaxation paths [8] for thermalization of carriers trough deep level defects introduced by displacement damage might enhance the luminescence emission from QDs. The impact of some of these findings in different space relevant nano-technologies is examined.

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This research was sponsored by the Jet Propulsion Laboratory, under a contract with the National Aeronautics and Space Administration.

Objective/Motivation

To compare the effects of 3-dimensional and 1-dimensional quantum confinement on radiation hardness.

Why? Some of the fundamental properties of QDs suggest that optoelectronic devices incorporating QDs could tolerate greater radiation damage than other heterostructures.

Approach

The photoluminescence (PL) emission from equivalent InGaAs/GaAs quantum well (QW) and quantum dot (QD) structures are compared after controlled irradiation with 1.5 MeV proton fluxes.

[redacted]

After deposition of GaAs buffer layers at 650°C, the temperature was lowered to 550°C and nanometer sized InGaAs islands were grown by depositing ~ 5 ML of $In_{0.6}Ga_{0.4}As$ using MOCVD. QW samples were obtained by stopping the growth of InGaAs before the onset of the Stranski-Krastanow transformation, giving thin (1 nm) QWs.

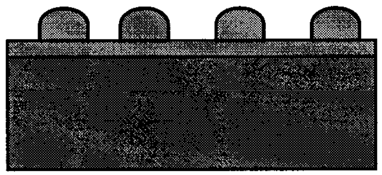
Ternary compositions between the samples were identical, and so was the capping layer thickness (100 nm for both QDs and QWs), therefore these results are not dependent on material or proton energy loss differences.

Force microscopy and transmission electron microscopy have been used to give information InGaAs QDs sizes and surface densities.

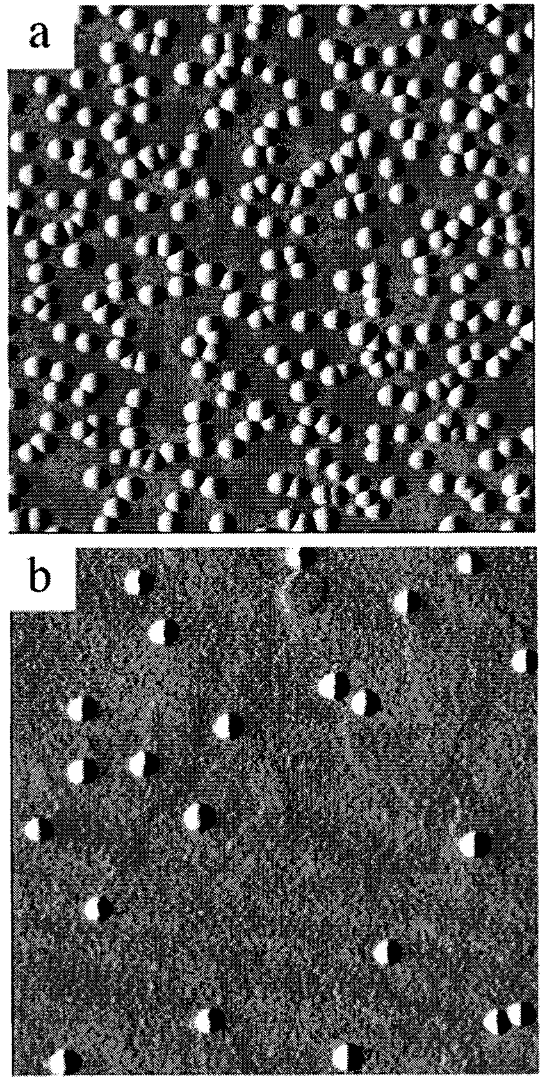
Proton irradiations were carried out using a Van De Graaff accelerator. Samples were irradiated at room temperature using 1.5 MeV protons at doses ranging from 7×10^{11} to $2 \times 10^{15}/cm^2$, with a dose rate of 6×10^{12} protons/sec.

Variable temperature photoluminescence (PL) measurements (from 4 K) were done using the 514 nm line of an Argon ion laser for excitation and a cooled Ge detector with lock-in techniques for signal detection.

Stranski-Krastanow Quantum Dots



This type of growth occurs for crystals of dissimilar lattice parameters but low interfacial energy, like **Ge on Si** and **InAs on GaAs**. After an initial layer-by-layer growth, islands form spontaneously, leaving a thin "wetting layer" underneath.

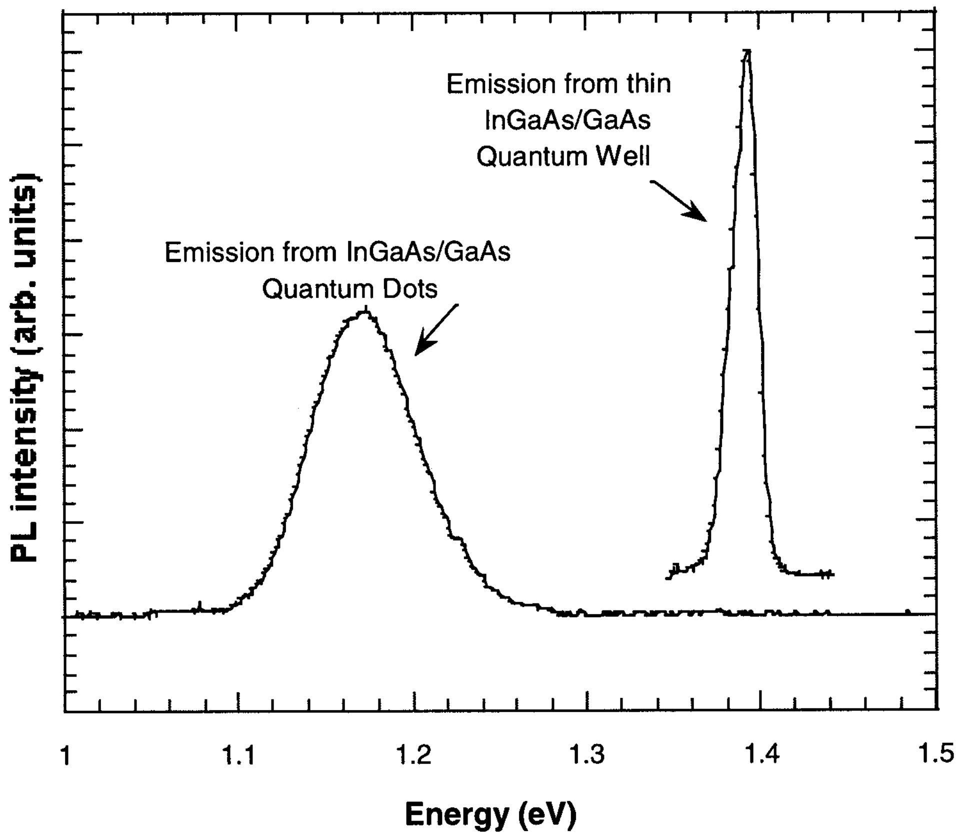


Self-forming InGaAs/GaAs QDs surface coverage range from 5% to 25%, depending on growth conditions →

[R. Leon, C. Lobo, J. Zou, T. Romeo, and D. J. H. Cockayne, *Phys. Rev. Lett.* **81**, 2486 (1998)]

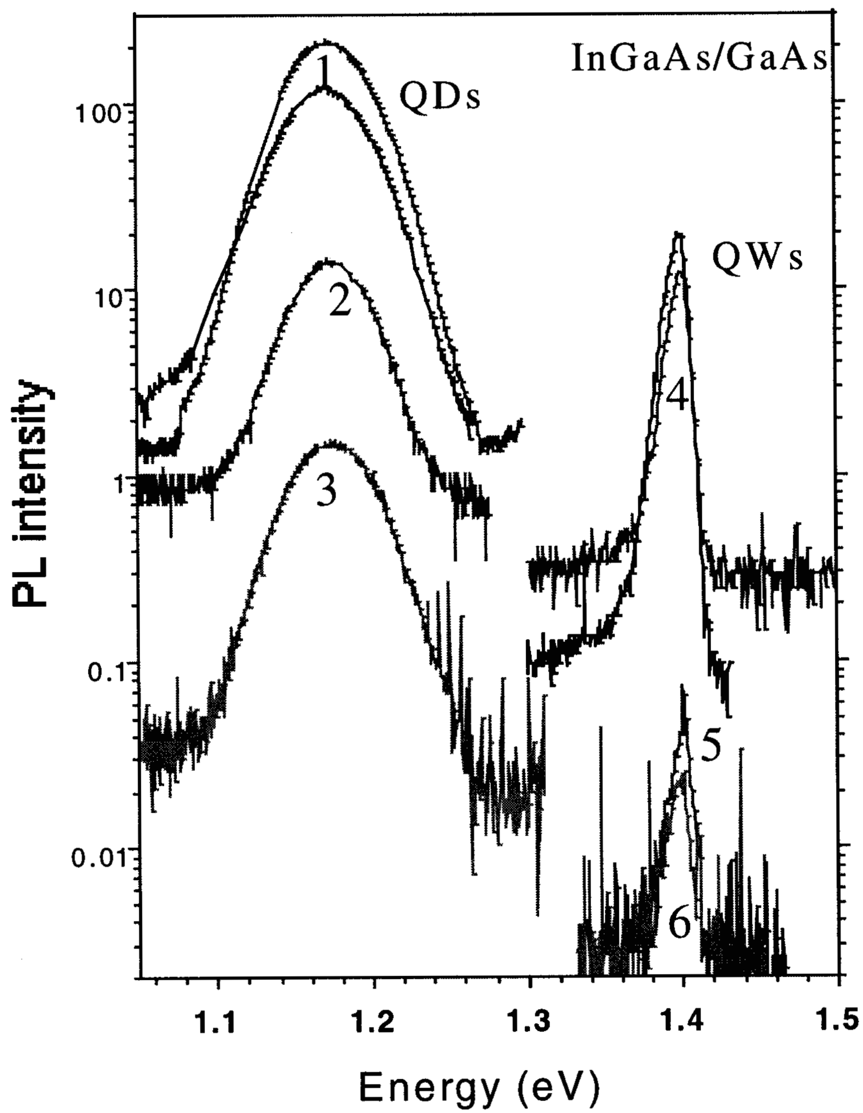
Boxes are 1 x 1 microns

Low temperature (77 K) photoluminescence spectra for InGaAs/GaAs quantum wells and quantum dots.



Differences in the PL emission prior to proton radiation:

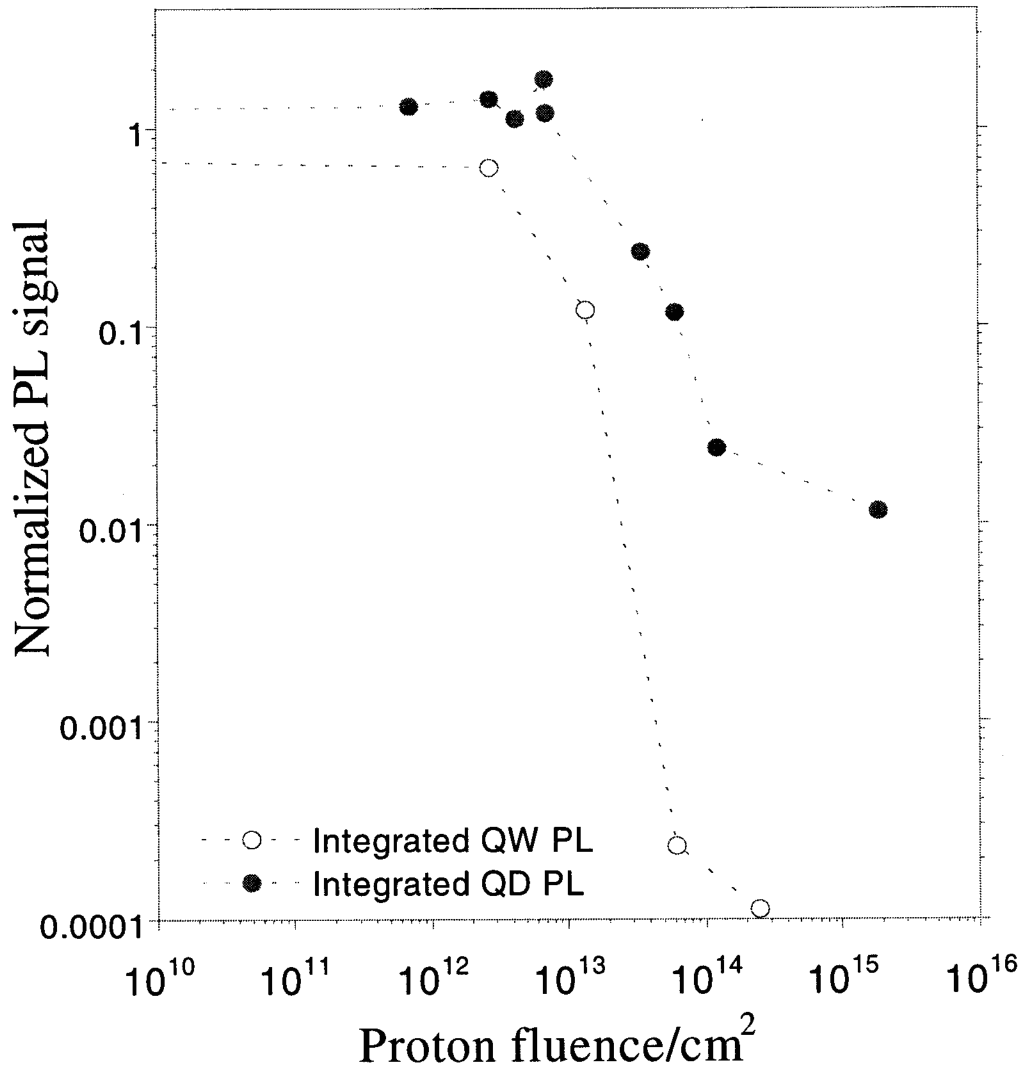
- Peak from QW is at higher energy (very thin ~ 1nm)
- Peak from QD is broader:
  1. Because of slight size fluctuations
  2. Because of positional disorder in dense dot ensembles



1.5 MeV protons /cm^2

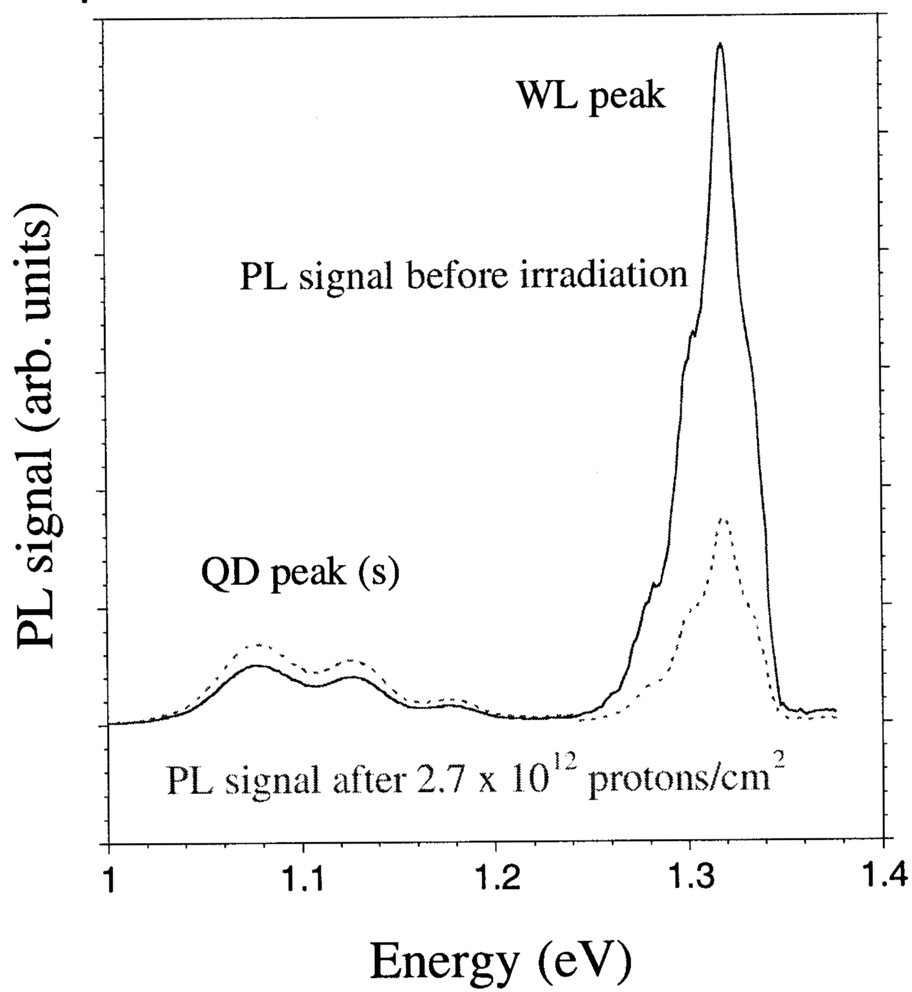
1) 7 x 10^{12},
2) 6 x 10^{13},
3) 2 x 10^{15},

4) 3 x 10^{12},
5) 6 x 10^{13},
6) 2 x 10^{14}



From: <u>Changes in Luminescence Emission Induced by Proton Irradiation: InGaAs/GaAs Quantum Wells and Quantum Dots</u>, R. Leon, G. M. Swift, B. Magness, W. A. Taylor, Y. S. Tang, K. L. Wang, P. Dowd, and Y. H. Zhang, submitted for publication.

Effects of proton irradiation in low density QD structures



Low surface density QDs (here 3-4 x 10^8 dots/cm^2) show distinct features: strong WL emission, emission from excited states and they are red shifted with respect to dots in high surface densities [R. Leon, S. Marcinkevičius, X. Z. Liao, J. Zou, D. J. H. Cockayne, and S. Fafard, *Phys. Rev. B* 60, R8517 (1999)]

Significant enhancement in radiation tolerance with three-dimensional quantum confinement

Why is this?

Total volume percentage of active QD region is very small (5% to 25%, depending on growth conditions) Exciton localization in the quantum dots due to three-dimensional confinement (here QDs are 5 nm height and 25 nm diameter) will reduce the probability of carrier non-radiative recombination at radiation induced defect centers. Small chance of finding radiation-induced defects in the active region.

Are there other effects?

Slight increase in QD integrated PL (from ~ 10% to 70%) with low to intermediate proton doses (from 7×10^{11} to $7 \times 10^{12}/cm^2$)

No such increase is observed in the QW structures: PL enhancement is an effect of three-dimensional confinement

Reduction of the phonon bottleneck by defect assisted phonon emission has been proposed as a mechanism to explain the bright PL emission in QDs [P. C. Sercel, *Phys. Rev. B* **51**, 14532 (1995)]

In quantum dots with defect free interfaces, introduction of deep level defects as those originated from displacement damage might provide additional relaxation paths for thermalization of carriers and therefore increase the luminescence emission [H. Benisty, C. M. Sotomayor-Torres, and C. Weisbuch, *Phys. Rev. B* **44**, 10945 (1991)]

What are the mechanisms responsible for the small degradation observed in the optical emission from QD structures (> $10^{13}/cm^2$) ?

The degradation in minority carrier diffusion lengths expected in the barrier and wetting layer materials is the most probable cause for the initial degradation observed in QD PL at higher proton doses and will contribute to any observed degradation in QD PL emission, by limiting carrier capture into the dots. This is most likely to take place before effects from direct damage in the dots becomes a significant mechanism for optical degradation.

Recent results for Quantum Dot Lasers

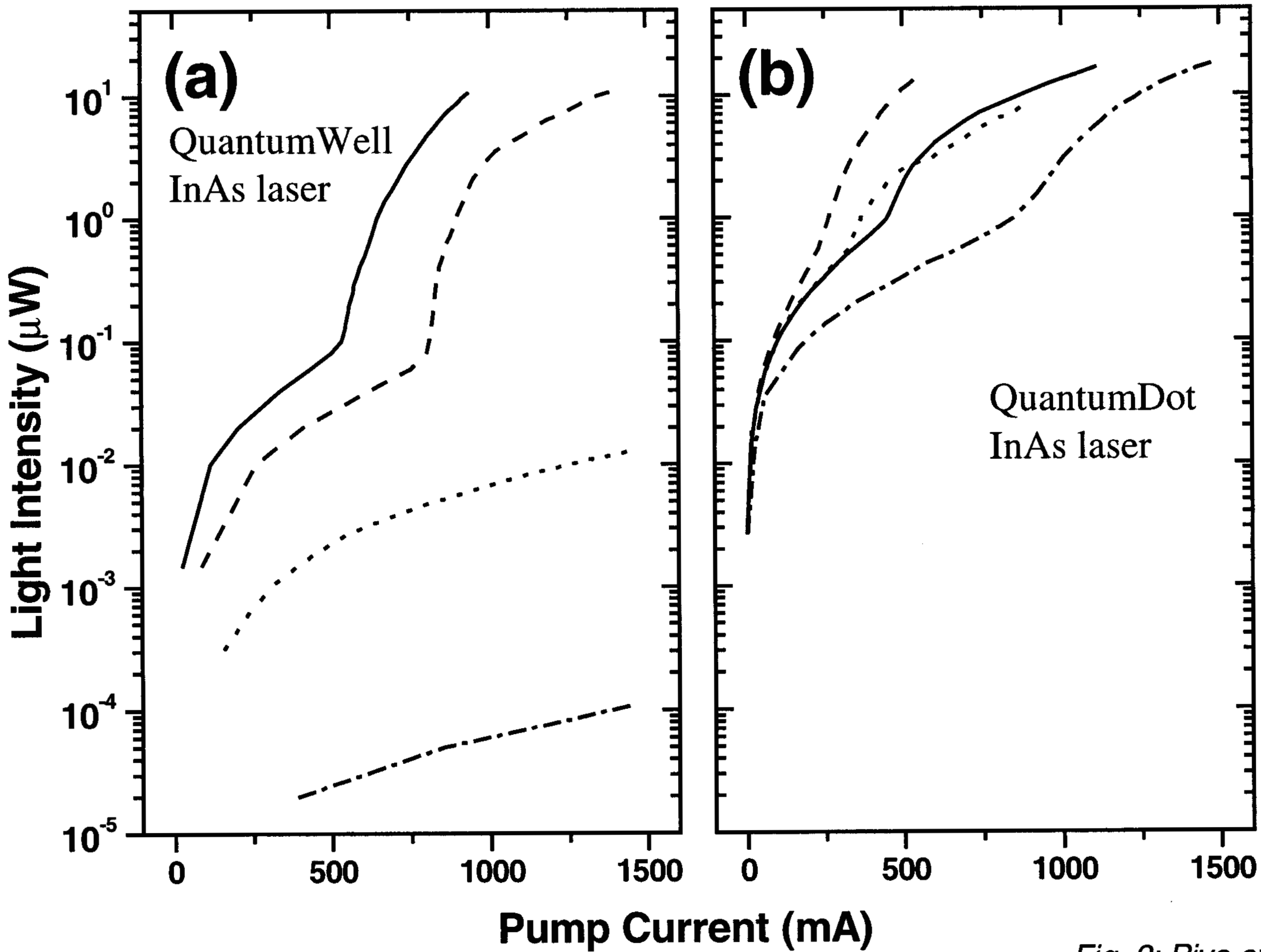


Fig. 2: Piva et al.

***Results obtained with 8.5 MeV Phosphorus ions - for more information see: Enhanced Degradation Resistance of Quantum Dot Laser Diodes and Detectors to Radiation Damage**, by P.G. Piva, R.D. Goldberg, I.V. Mitchell, D. Labrie, R. Leon, S. Charbonneau, Z.R. Wasilewski, and S. Fafard, submitted for publication*

Impact on Quantum Dot based devices:

Quantum Dots can be exploited in these applications:

Based on these results we expect greater radiation tolerance from:

- ✓ QD Lasers with lower threshold current and higher gain

- ✓ QD Infrared photodetectors with reduced dark current

More radiation testing is needed to determine if QDs will make the following devices radiation hard:

Ultra-high density optical memories (frequency domain optical storage based on persistent spectral holeburning)

Computing through ordered Quantum Dots (cellular automata)

Conclusions/Summary of Results

QDs structures are inherently more radiation tolerant due to the effects of three dimensional quantum confinement. We observe an increase in radiation hardness of as much as two orders of magnitude over QW structures.

A slight increase in PL emission from InGaAs/GaAs QDs can be observed with low to moderate proton doses.

Radiation induces subtle changes in the temperature dependence of the luminescence emission from InGaAs quantum dots.